Electric and Magnetic Dipole Measurement of the Muon

Gerco Onderwater

KVI, Groningen, The Netherlands

Dipole Moments in a Nut Shell

Dipole moments are aligned along the spin:

$$\vec{\mu} = g \frac{e\,\hbar}{2\,m\,c} \vec{S} \qquad \vec{d} = \eta \frac{e\,\hbar}{4\,m\,c} \vec{S}$$

The electric and magnetic dipole moments can be related to each other as the real and imaginary part of a more general dipole moment $\vec{D}$.

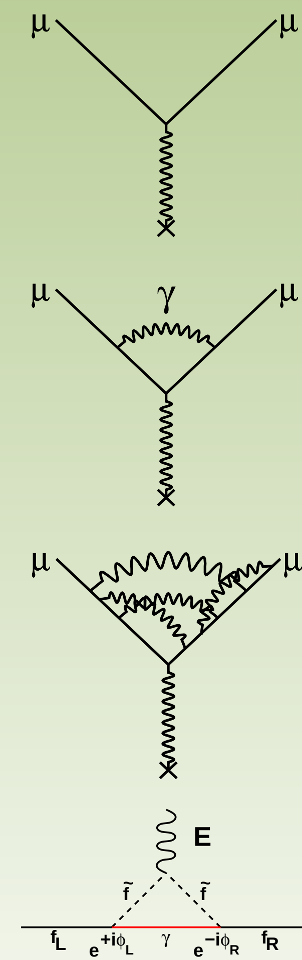
Experimentally accessible through the interaction with a magnetic and electric field:

$$\mathcal{H} = -\left(\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}\right) \qquad \vec{\tau} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

EDM & MDM Probe Radiative Corrections

	MDM (g)	EDM (η)
Tree level	2	0
QED	+ 0.002$\cdots$	0
Hadronic	+ 0.00000012$\cdots$ *	0
Weak	+ 0.000000003$\cdots$	0
HO Weak+Hadr.	.....	$\simeq 10^{-22}$
Theory	2.0023318366(14)	$\simeq 10^{-22}$
Experimental	2.0023318416(12)	$< 6.0 \times 10^{-6}$
NEW PHYSICS	$\leq$ 5 ppb	$\simeq 10^{-9}$

*Preliminary result presented by A. Höcker at ICHEP'04

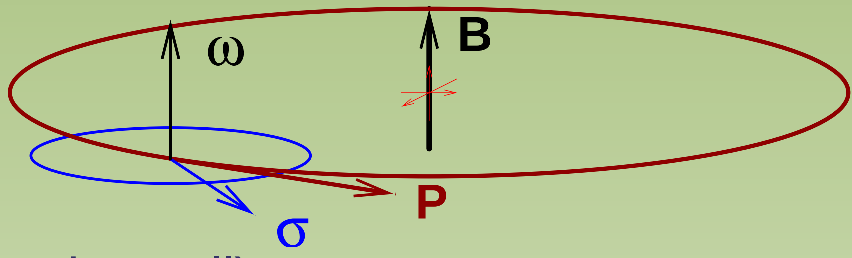


Excellent tool to study fundamental interactions!!!

Measurement Principles

1. Prepare highly polarized ensemble of muons
   - produce π's with high energy protons
   - $\pi \rightarrow \mu\,\nu_\mu$
2. Let the muons interact with B and/or E for as long as possible
   - electromagnetic storage ring
   - BMT: $\vec{\omega} = \frac{e}{m}\left[a_\mu \vec{B} + \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B} + \vec{E}\right)\right]$
3. Measure the evolution of the spin orientation
   - Use analyzing power in $\mu \rightarrow e\,\nu_\mu\,\nu_e$

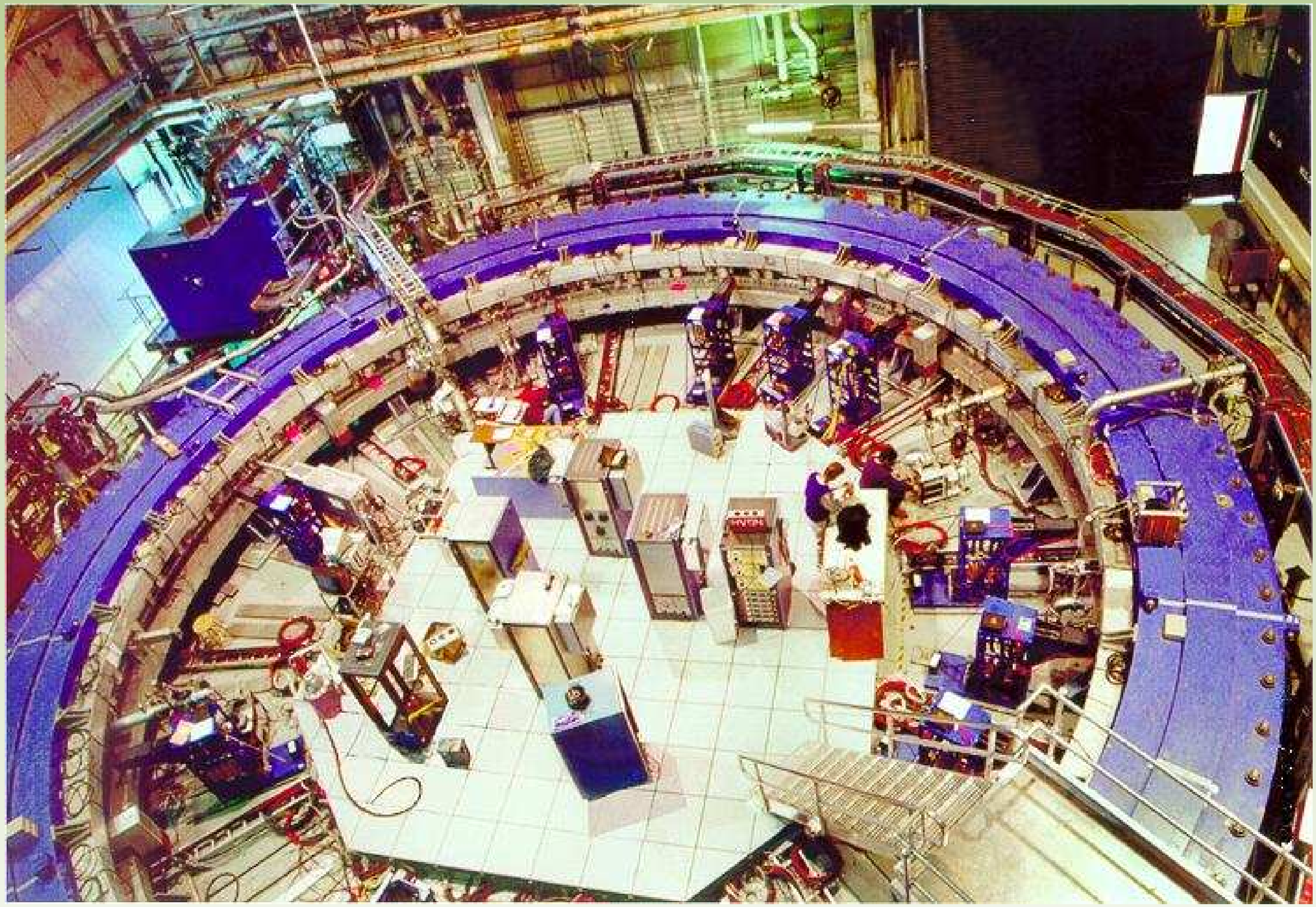
MDM measurement



- Measure $a = (g-2)/2$ (we know “2” quite well)
  - Pick $\gamma \simeq 29$, so that $a_\mu - 1/(\gamma^2 - 1) = 0$
    - Use a homogeneous magetic field B (easy to measure)
      - Focus beam with a quadrupole E (no need to measure)
        - Assume $\eta = 0$

$$\vec{\omega}_a = \frac{e}{m} a_\mu \vec{B}$$

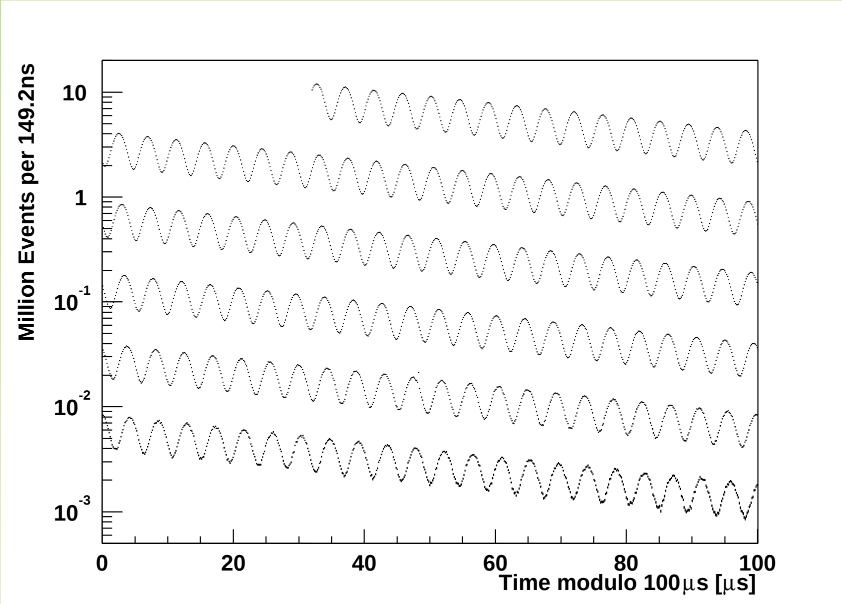
The E821 muon $g - 2$ Experiment at BNL



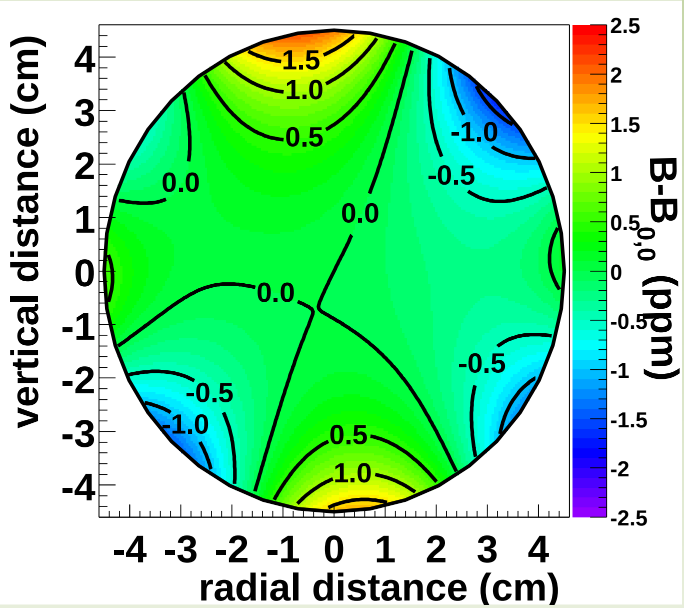
B = 1.45 T $\quad$ R = 7.11 m

Data Sample

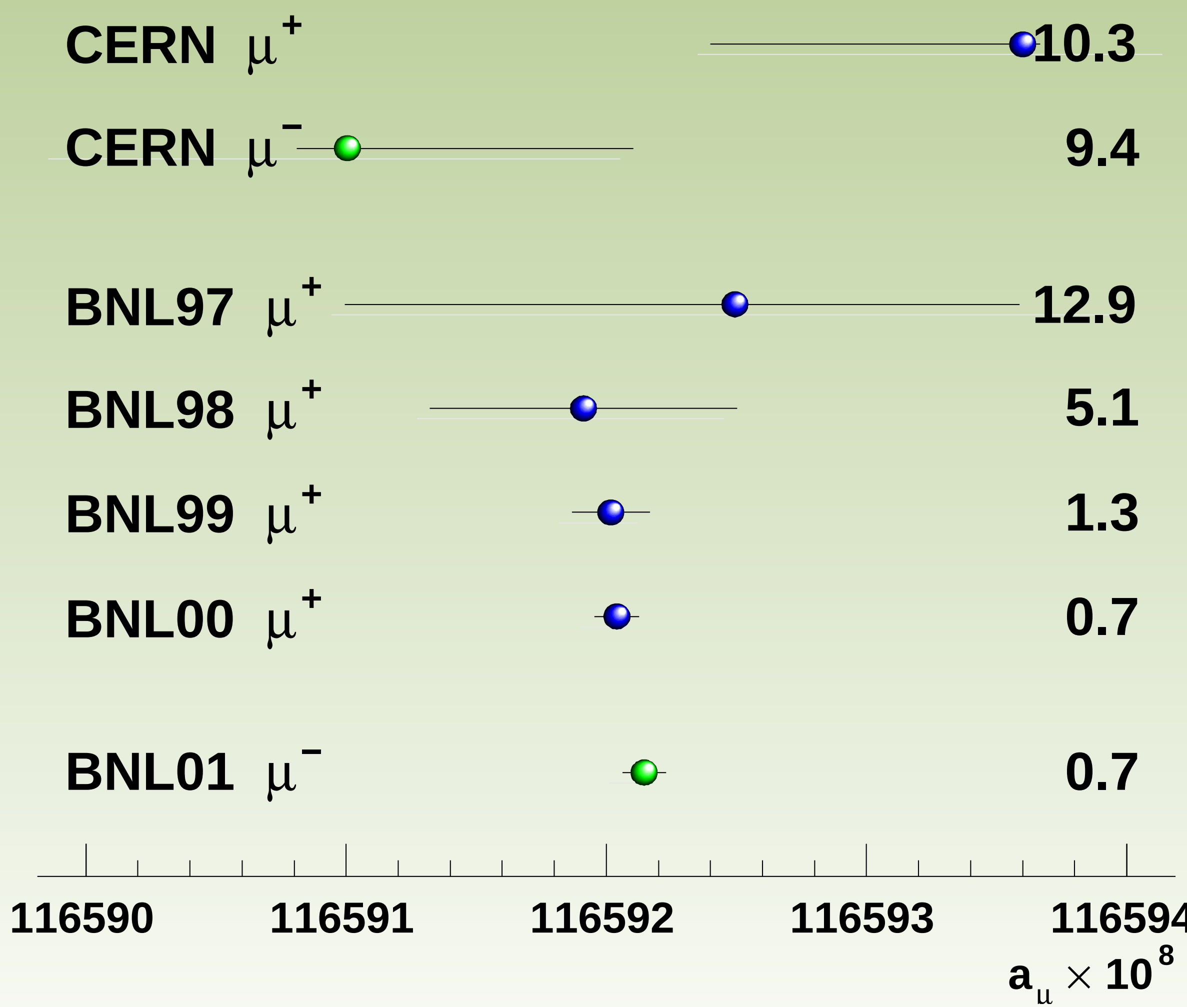
ω_a



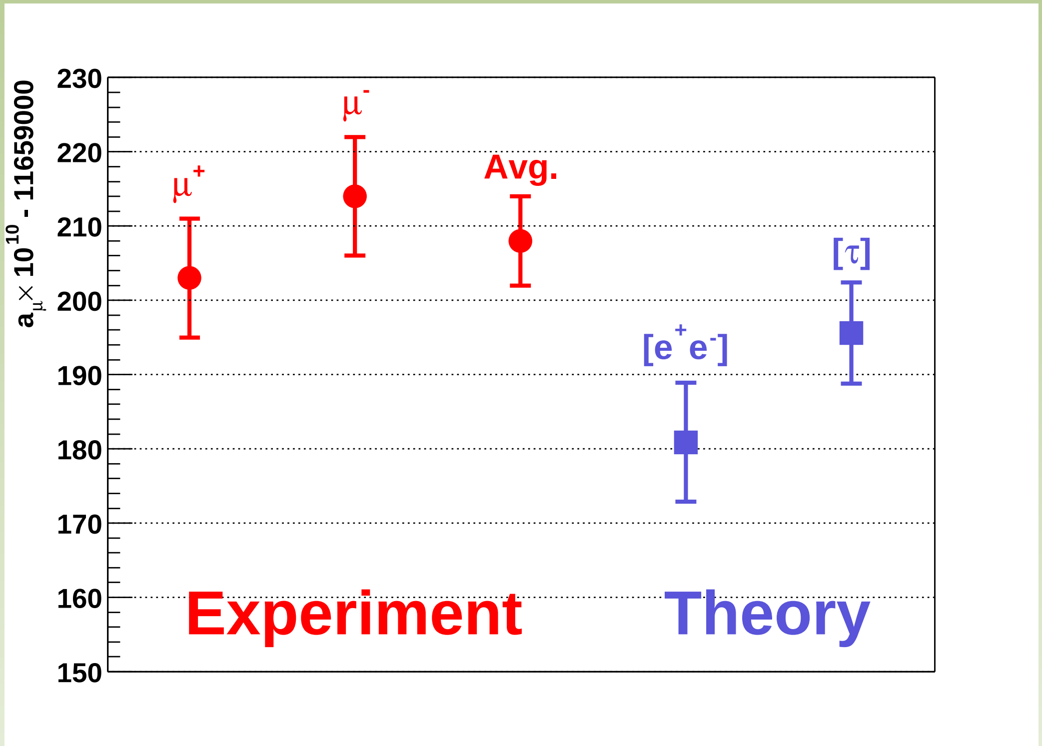
B



The History of a_μ



Experiment and Theory Comparison



The difference is 0.9 – 2.7 (combined) standard deviations

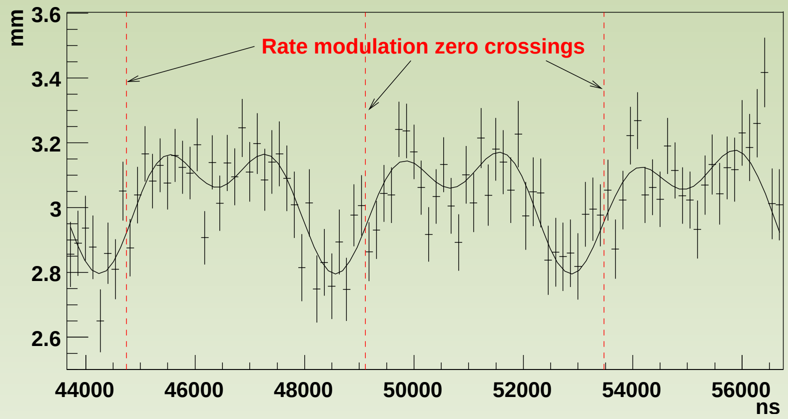
Experimental result is statistics limited; request for additional beamtime at BNL is in; LOI for new experiment at J-PARC has been submitted

EDM measurement in E821

$$\vec{\omega} = \frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\vec{\beta} \times \vec{B}\right]$$

$\rightarrow \omega = \frac{e}{m}\sqrt{a_\mu^2 + (\eta\beta/2)^2}\, B$

$\rightarrow$ vertical rate modulation



$d_\mu < 2.8 \times 10^{-19}$ e·cm at 95% C.L. (syst.)

Dedicated EDM Experiment

Novel technique: “freeze” the MDM comtribution to the spin precession with a radial electric field. For $E_r \simeq a\, B\, c\, \beta\, \gamma^2$:

$$\vec{\omega}_\eta = \frac{e}{m}\frac{\eta}{2}\left(\vec{\beta} \times \vec{B}\right)$$

Typical parameters:

E	B	p	γ	τ	R
2 MV/m	0.25 T	0.5 GeV/c	5	2.2 μs	7 m

Need of the order of 10^{16} muon-decays $\Rightarrow$ high-intensity muon source indispensible. LOI to J-PARC submitted.

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Conclusion and Perspective

- The muon is an excellent tool to study the properties of fundamental interactions
- The measurement and calculation of the (anomalous) magnetic dipole moment have reached a sub-ppm level and leave only little room for ‘new physics’ (2.7σ)
- Calculation of the hadronic constribution the largest uncertainty
- Experiments for improved precision planned at BNL and J-PARC
- The SM muon EDM is essentially zero, but “new physics” contributions may be with the experimental reach
- Parasitic measurement of the EDM in the E821 experiment has improved the EDM limit by a factor 3 down to 2.8×10^{-19} e·cm
- A novel experimental technique is being developped to improve the EDM limit by 4–5 orders of magnitude. LOI submitted at J-PARC

From A. Höcker @ ICHEP'04

Conclusions and Perspectives

- Hadronic vacuum polarization is dominant systematics for SM prediction of the muon $g - 2$
- New data from KLOE in fair agreement with CMD-2 with a (mostly) independent technique
- Discrepancy with τ data (ALEPH & CLEO & OPAL) confi rmed
- Until τ / e^+e^- puzzle is solved, we use only e^+e^- data in dispersion integral
- We fi nd that the SM prediction differs by 2.7σ [e^+e^-] from experiment (BNL 2004)

Future experimental input expected from:

- New CMD-2 results forthcoming, especially at low and large $\pi^+\pi^-$ masses
- BABAR ISR: $\pi^+\pi^-$ spectral function over full mass range, multihadron channels ($2\pi^+2\pi^-$ and $\pi^+\pi^-\pi^0$ already available)
- New proposal submitted by E821 Collaboration aiming at precision of 2.4×10^{-10}
- Ambitious muon $g - 2$ project at J-PARC, Japan, aiming at (0.1 - 0.2) $\times$ σ(BNL-E821)